XII. *Electro-Physiological Researches.—Second Memoir. On the proper Current of the Frog. By Signor* CARLO MATTEUCCI, *Professor in the University of Pisa, &c. &c. Communicated by* MICHAEL FARADAY, *Esq., F.R.S., &c. &c.*

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IN the seventh chapter of my Traité des Phénomènes Electro-Physiologiques des Animaux, after having examined all that GALVANI, HUMBOLDT, VALLI, and more recently NOBILI, have said on this subject, I mentioned all my own researches from which the laws of this phenomenon follow. Comparing the muscular and the proper current together, we find that the influence of the different circumstances affects both currents equally. Thus it is that both the muscular and the proper current vary in the same sense with the variation of the temperature of the medium in which the frogs live. Sulphuretted hydrogen diminishes the proper current just as it does the muscular current. The same may be said of the effects produced upon the proper current by the different degrees of activity of the respiration and of the circulation of the blood. I shall not here mention all the numbers obtained in the experiments recently performed upon the proper current of the frog. I will merely say that I followed up every one of the experiments on the muscular current referred to in this memoir, with another experiment on the proper current, composing the pile with the legs which remained after having prepared the frogs for the muscular current. After so great a number of facts, I do not hesitate in repeating what I have said in page 127 of my Treatise: "comparing one with the other the circumstances which exert an influence over the muscular and over the proper current, they may be said entirely to resemble one another, and that that which increases or weakens the intensity of one of these currents, produces the same effect upon the other." Two points, however, still remain to be cleared up. Do the circumstances which affect these two currents operate upon both in a like degree? or in other words, does that circumstance which diminishes as well the muscular as the proper current of the frog, act proportionally in that diminution?

I had found in my first experiments, that comparing two piles, one consisting of half thighs of frogs, the other of entire or halves of frogs, so as to obtain the proper current, the signs produced by the latter pile continued longer than those evinced by the muscular pile.

I then began to renew my former experiments for the purpose of convincing myself of the reality of this difference, the only one between the muscular and the proper current.

Studying afresh the influence of the various circumstances (temperature, respira-

tion, sanguineous circulation, sulphuretted hydrogen) upon the proper current compared with the muscular current, I came to the following conclusion: the diminution which occurs in the intensity and duration of the proper current, from the decrease of temperature, from defect of respiration and the sanguineous circulation, and from the action of sulphuretted hydrogen, is considerably greater than that which takes place in the intensity and duration of the muscular current. Thus, with the same number of elements, I have always seen that the proper current has been considerably weaker than the muscular current, operating on frogs asphyxiated, killed with sulphuretted hydrogen, or in the coldest weather. This difference decreases in proportion to the robustness and vivacity of the frog, so that in the spring and summer, choosing very strong frogs, the signs of intensity and the duration of the proper current equal and even surpass those of the muscular current.

I was desirous of again studying the proper current in piles composed either of legs alone or of half thighs of frogs, or of entire frogs (figs. 5. 7. 8). In general, as I found before in my former experiments, these three piles produced currents the intensity of which was sensibly alike in all. This coincidence seems at first rather singular, considering the diversity of the internal resistance of the three piles, and admitting that the electro-motor element of the proper current resides in the leg alone. The experiments which I shall report at the close of this memoir, explain this fact sufficiently clearly.

Comparing, however, the three above-mentioned piles, composed from frogs which had been exposed previously to the action of debilitating causes, I have always found that the signs of the proper current, in the pile composed of the legs alone, somewhat exceeded those of the other piles.

I would here refer to another experiment, described at page 116 of my Treatise, performed with a pile (fig. 6.) of half frogs, from which the upper half of the thigh had been taken away. In this pile the proper current is in opposition to the muscular current, for which reason the current obtained is very weak, and sometimes null. I have still, however, constantly observed that if the frogs employed for this experiment are very robust, and in those conditions which we have seen to be favourable to the proper current, the signs of a current which this pile gives, though always very weak, are in favour of the proper current; while, on the contrary, when the frogs are taken in the conditions unfavourable to the proper current, the slight current which this pile gives are in favour of the muscular current.

From the sum of these facts I am again forced to conclude, as I was led by my former experiments to do, that the proper and the muscular current are in general subjected to the same laws, and that both these currents vary in the same sense, under the same circumstances.

But why should the proper current belong exclusively to the frog? This is the problem the solution of which I had long been anxious to arrive at, and hope finally to have given a satisfactory explanation.

Fig. 8.

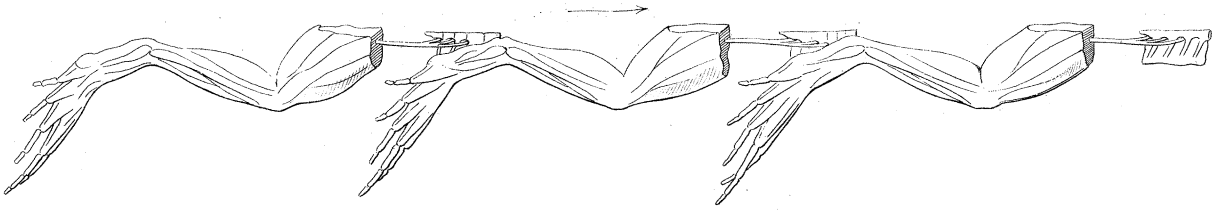


Fig. 9.

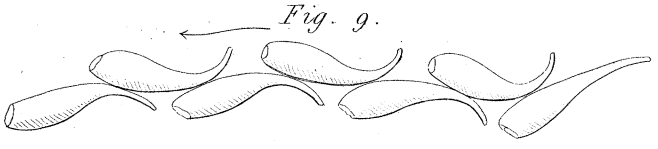


Fig. 10.

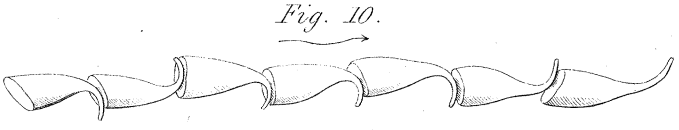


Fig. 11.

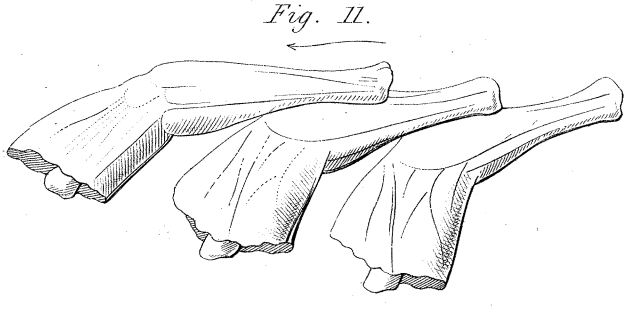


Fig. 12.

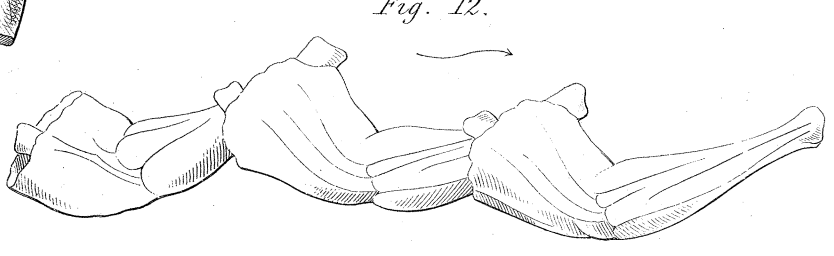


Fig. 13.

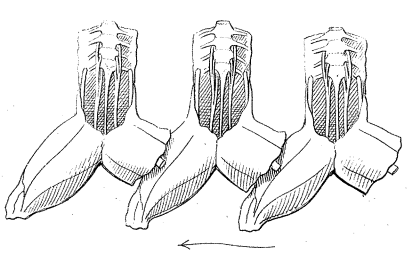
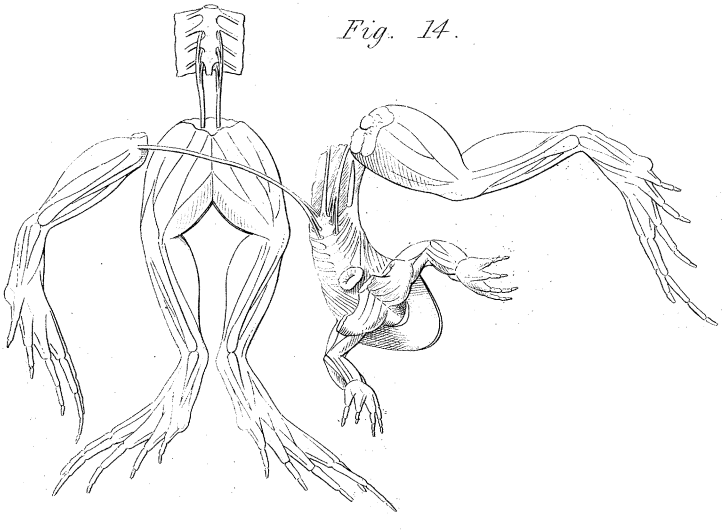


Fig. 14.



I had frequently observed, while operating with great rapidity upon rabbits, fowls, and pigeons, that the signs of the proper contractions frequently manifested themselves, and that therefore the celebrated experiment of GALVANI was repeated in warm-blooded animals. When the thighs are cut away from these animals, the nerve laid bare, and folded back upon the leg, contraction is frequently visible. These contractions are more constantly obtained by composing piles of these thighs and making the nerve touch the leg. I must say, however, that every time that I have composed a pile of such thighs, I have obtained the signs of the muscular current, for which reason the contractions might have been attributable to that current.

Let it be remembered, however, that in composing these piles, it is impossible not to put the current which parts from the internal surface of the muscle in circulation, for which reason a pile should be made analogous to that of the half frogs divided at the upper half of the thigh (fig. 6.). Observation has shown, from the time of GALVANI, that the points of the leg of the frog to be touched, for the purpose of producing the proper contraction, are the points of insertion of the surface of the funicular tendon of the gemellus or gastrocnemius muscle into the calcaneum.

In one experiment, described at page 105, I had endeavoured to remove the tendinous surface of the muscles of the legs, then composing the pile with the frogs so prepared, I had the current as at first, that is, directed from the feet to the head, in the animal. This experiment, however, did not prove that the proper current exists independently of the tendinous surface of the muscle; in fact, removing the tendon, I lay bare the muscle, and so doing prepare a muscular pile, in which the current, being directed from the interior to the exterior of the muscle, is therefore in the same direction as the proper current.

The following are the experiments which led me to generalize the fact of the proper current of the frog. There is no difficulty in preparing the gemellus or gastrocnemius muscle of the frog, leaving a certain portion of the funicular tendon, or tendo Achillis, which goes on to insert itself into the calcaneum, and taking care to avoid as far as is possible injuring the upper part of the muscle. I prepared a great number of these elements, and arranged them in a pile, as represented in Plate IV. fig. 9, in such a manner that the tendinous extremity came in contact with the belly of the muscle. From this pile I obtained signs of a current directed in the muscle from the tendon to the muscle, that is to say, in the same direction as the proper current. Comparing together an equal number of elements arranged in piles, and consisting of legs alone, or of gastrocnemius muscles only, the intensity of the current has been to all appearance the same.

With equal facility the rectus femoris of the frog may be prepared, leaving the tendinous extremity which is inserted into the patella, and laying bare as little as possible of the internal muscular surface of the upper part. Thus I have been enabled to form a pile composed of several recti femoris, always arranging them in such a manner that the tendinous extremity reposed upon the surface of the muscle as far

removed as possible from the internal part. A pile so formed has given constant and distinct signs of a current directed in the muscle from the tendon to the muscle. With regard to the intensity, I must add that the signs have always been weaker, from the pile composed of recti femoris, than those from the pile of half legs or gastrocnemii muscles.

It is very natural that the cause of this difference should be owing to the fact of the muscular current circulating in a contrary direction to the other. And, in truth, if the disposition of the elements which compose these piles be ever so little changed, so that the tendon of one of these elements be made to repose upon or near to the interior of the muscle, the signs of every current become very weak or cease altogether (fig. 10.).

I have prepared a number of anterior cubital muscles, or muscles of the fore-arm of frogs, which likewise have at their extremities, near the carpus, a very distinct tendinous band. A pile composed of these muscles, disposing them as usual, with the tendon resting on the muscular surface of the next element, gives constant and very distinct signs of a current, the direction of which, in the muscle, is from the tendon to the muscle. The following in the meanwhile is the generalization of the fact of the proper current of the frog: the current is directed within the muscle from the tendon to the superficies.

It remained for me to extend this fact to its operation upon the muscles of warm-blooded animals, and the experiments accorded in such a manner as to leave no possible doubt.

In these experiments I employed fowls, pigeons, rabbits and dogs. It is necessary to operate with great rapidity upon these animals, since, as in the muscular current, the signs of the current which we are now studying cease very quickly. Not less than six or eight elements are necessary for eliciting signs of this current sufficiently evident to remove all doubt. In all these animals the muscular extremities turned towards the feet are furnished with tendons much more distinct and grouped together than those of the upper and opposite extremities. I wished at first to have separated the different muscles as I had done those of the frogs, but the process is much more difficult with the muscles of these animals, which always get considerably lacerated.

In order to succeed in the best possible manner, after having removed the integuments, I cut the thigh as near as possible to the articulation with the os ilium; and in pigeons it is easy to tear the thigh out of the socket. The surface of these elements should be well-dried and the pile formed (fig. 11.), disposing them in such a manner that the inferior extremity of the leg, where the tendons unite together, reposes upon the surface of the muscular masses of the leg. In this manner the muscles of the thigh have no part in the circuit. From similar dispositions of eight elements taken from rabbits or pigeons, the signs of a current, marked by my galvanometer, were from 12° to 15°, and 20°, and directed in the pile from the tendinous extremities

to the muscular surfaces. It is sufficient to introduce the thighs into this pile, to put, that is to say, the interior of the muscle in contact with the tendinous extremity, for the sign of the current to be inverted, and the muscular current produced (fig. 12.). This proves how necessary it is, in order to have the signs of the current directed from the tendon to the muscle, not to comprehend any portion of the interior of the muscle in the circuit.

Let us then conclude, that "touching a mass of muscle belonging to a living animal, or an animal recently killed, with a homogeneous conducting arch, one extremity of which is contact with the tendon of the muscle, and the other with the superficies of the muscle itself, signs of an electric current are obtained, which circulates in the muscular mass, its direction being from the tendon to the external surface of the muscle."

This fact comprehends that of the proper current of the frog.

Let it not be forgotten that from the sum of all our researches, it has been proved that both the muscular and proper current are subject to the same laws, and thus in all probability have a common origin. I would here again call the attention of anatomists to the study of the structure of the muscles, and of the relation which exists between the muscular fibres, the tendon, and the membrane which invests the fibres or the sarcolemma.

If I have rightly understood the classical labours of my friend Mr. BOWMAN, it would follow that the extremities of the elementary muscular fibres are immediately connected and continued with the tendinous fibre; while the sarcolemma which invests the muscular fibre ceases abruptly where the tendon begins. On the strength of this disposition I cannot abstain from emitting an hypothesis upon the origin of the proper current, which would reduce all that we know on the subject of animal electricity to one principle alone. Let it be granted that the tendinous fibre, from its structure, from its connections with the muscular fibre, and from its conductibility, represents the internal part of the muscle, and that the sarcolemma, on the contrary, is distinguished under this aspect from the muscular fibre; then the case of the proper current, or of the current from the tendon to the muscular surface, becomes at once the simplest and most general case of the muscular current. We must never forget the analogy between the muscular electro-motor element and the Voltanian element: the zinc is represented by the discs of the muscular fibre, the acid liquid by the blood, the platinum by the sarcolemma. Whatever be the conducting body with which the zinc is made to communicate with the platinum, the current is always in the same direction. If it be well proved by anatomy that the tendinous extremities are continuous with the extremities of the muscular fibres, and that the sarcolemma which envelopes the muscular fibre alone, and not the tendon, is not continuous, is not as it were identified with the muscular fibre, the analogy between the muscular element and that of VOLTA is complete and perfect.

The chemical actions of nutrition evolve electricity.

Pisa, April 7, 1845.